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ScienceDirect
Energy Procedia 88 (2016) 775 – 780
Energy Procedia

CUE2015-Applied Energy Symposium and Summit 2015: Low carbon cities and urban energy systems

How Does Building Occupancy Influence Energy Efficiency of HVAC Systems?

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Abstract

Occupancy (presence and number of occupants) is one of the most important factors impacting energy efficiency of HVAC systems as occupancy determines heating/cooling loads on the demand side by varying conditioning periods and settings. Despite the high volume of research activities in demand-driven HVAC controls, how and when occupancy should be linked with heating/cooling loads for sustained and maximum efficiency are still not clear as occupancy is stochastic in nature, and there exists heat transfer and balance among zones, as well as heat gain and loss through a building's envelope. There is no solution to date that can be directly applied in different buildings with different HVAC systems and occupancies. This paper systematically investigates how the occupancy influences the energy efficiency of HVAC systems. Specifically, the influence is analyzed from three perspectives of occupancy transitions, variations, and heterogeneity. The results demonstrated the energy significance of the three perspectives and provided the general ways of quantifying the influences of occupancy.

Peer-review under responsibility of the organizing committee of CUE 2015

Keywords: building occupancy; HVAC system; energy efficiency; occupancy characteristics; commercial building; loads

1. Introduction

In the U.S., approximately 40% of all energy consumption is attributed to buildings. In commercial buildings, more than 40% of energy is used by HVAC (Heating, Ventilation, and Air Conditioning) systems to maintain comfortable indoor thermal conditions [1]. There is great potential for energy efficiency if occupancy is considered to reshape the demands in the operations of HVAC systems and to minimize the difference between actual consumptions and demands. Energy efficiency incorporates both energy reduction, which is the absolute amount of energy savings, and conditioning miss, which is the length of time a space is occupied but the temperature is outside the comfort range. For each thermal zone, the setpoint regulates the desired temperature range and acts as the primary parameter for controlling the interactions among HVAC system response, indoor thermal conditions and occupancy. Since a typical

Peer-review under responsibility of the organizing committee of CUE 2015
doi:10.1016/j.egypro.2016.06.111

HVAC system responds to heating/cooling loads through the control of setpoints, setpoint is used in this paper as the medium to analyze the influences of occupancy on energy efficiency.

Even though extensive research has been conducted to improve HVAC system control by only responding to actual occupancy, the significance and form of influences that building occupancy put onto energy efficiency are still not clear. Basically, occupancy has patterns but it is stochastic in nature and has variety, resulting in random variations and variant transitions for different days. Besides, occupancy of different spaces is heterogeneous and might be distinct. This paper conducts a systematic research for analyzing the influences of occupancy on HVAC energy efficiency from three perspectives of occupancy transitions, variations, and heterogeneity, based on the occupancy characteristics.

2. Building occupancy and energy efficiency

The importance of occupants to HVAC energy efficiency can be broken down into two categories: Occupancy in a building (how occupants occupy a building) and occupant actions in a building (how occupants behave in a building) [2]. Occupancy is defined as time-sequenced occupancy changes for a space, including presence and number of occupants. Occupancy results in heat gain due to occupants' metabolisms and activities, and is associated with the use of building systems (e.g., lighting system) and appliances (e.g., computers), which also add heat to the environment. Occupant actions impact HVAC energy efficiency through the occupant interactions with building elements (e.g. adjusting windows and doors). Occupancy is the focus of this paper and can be further divided into two categories of real-time occupancy [3], which is the instant occupancy status, and long-term occupancy [4], which is the typical presence/number probability as a function of time for a predefined period of time (occupancy profile).

Occupancy transition is the switch between real-time occupied and unoccupied statuses. During an unoccupied period, allowing a setpoint to float to a different temperature (setback) could potentially reduce loads on the demand side [5]. The control at zone level could be divided into four periods based on occupancy transitions: the setpoint period: a terminal works to maintain the setpoint, loads are effective; the float period: a terminal is off and the temperature floats from setpoint to setback, loads are ineffective; the setback period: a terminal works to maintain the setback, loads are effective; the reconditioning period: a terminal works to restore temperature from setback to setpoint, loads are effective. Since the transitions between occupied/unoccupied statuses do not necessarily follow the transitions between effective and ineffective loads, a portion of the loads during unoccupied periods should be still considered effective for improving energy efficiency [6]. Therefore, the synergetic effects of setpoint/ setback schedules (waiting time to trigger setback) and distances (setback value) determine the influences of occupancy transitions on HVAC energy efficiency. *Occupancy variation* is the deviation between real-time occupancy and long-term occupancy since occupancy of different days is not static and deterministic. Real-time occupancy reflects the occupancy status for specific time and represents instant effective loads; while long-term occupancy indicates habitual patterns for different class of occupancy and represents typical effective loads. Real-time occupancy follows the trend of long-term occupancy with fluctuations. They are both vital to determine the variations in effective loads and influence the HVAC energy efficiency [7]. The degree of occupancy variation of a space is defined as the Euclidean distance between the actual daily occupancy versus the occupancy profile. Its relations with the daily energy reduction and conditioning miss of a specific HVAC control represent the influence of occupancy variations on HVAC energy efficiency. *Occupancy heterogeneity* is the difference in real-time occupancy among different spaces. At the zone level, real-time occupancy is the aggregation of the occupancy status of rooms in that zone. When only one room is occupied, heating/cooling is required for all of the room of that zone. It has been found rooms of buildings may have different or inverse occupancies [8]. Simply aggregating real-time occupancies might create an inaccurate representation of how each zone is occupied, and reduce energy efficiency because the periods of ineffective loads for one space might become effective due to the occupancy of other spaces within the zone [9]. Besides, there exist heat transfer and balance among zones. Zones form a network with some being served by the same supply air or having similar or shared boundary conditions. The reduction of effective loads from one zone could be compromised by the varied occupancy of other zones. All of these indicate that the occupancy heterogeneity may lead to the heterogeneous distribution of effective loads. The long-term occupancy should be integrated to redistribute effective loads through occupant reassignment in order to analyze the influences of occupancy heterogeneity on HVAC energy efficiency.

Even though extensive research has been conducted to improve HVAC system control by only responding to actual occupancy, the significance and form of influences that building occupancy put onto energy efficiency are still not clear. Basically, occupancy has patterns but it is stochastic in nature and has variety, resulting in random variations and variant transitions for different days. Besides, occupancy of different spaces is heterogeneous and might be distinct. This paper conducts a systematic research for analyzing the influences of occupancy on HVAC energy efficiency from three perspectives of occupancy transitions, variations, and heterogeneity, based on the occupancy characteristics.

3. Occupancy and energy

A real-world building was selected as the test bed building to validate the ways and significance of influences that occupancy has on HVAC energy efficiency from the three perspectives. It is a three-story building with a footprint of 3,735 m2 with 89 mechanically ventilated rooms that have spaces of varying sizes and functions. The building is equipped with a state-of-the-art Building Management System (BMS) and central HVAC AHU system. Energy data was recorded for every minute and occupancy data was obtained through occupancy modeling frameworks developed by the authors to investigate the relationships between occupancy and HVAC energy efficiency [3, 9]. A whole building simulation model was developed [10] for the test bed building as the venue for the investigation. The simulation periods were from March 2014 to March 2015. The results for the third floor were analyzed.

For *occupancy transitions*, the energy implications of discrete pairs of setpoint/setback schedules and distances (e.g., an interval of 5 minutes for schedule and an interval of 1 degree for distance) on conditioning miss and energy reduction were simulated. The results were visualized using gray maps (percentage of energy reduction and percentage of conditioning miss compared to the base control – maintain setpoint for entire working hours) (Fig. 1). The darker the color is, the more energy reduction and less conditioning miss are achieved. Depending on their relative importance (50% for each in this paper), final energy efficiency is expressed as a weighted sum of the two gray maps, which reflect the influences of occupancy transitions on HVAC energy efficiency. It is demonstrated that occupancy transitions have significant influences on the HVAC energy efficiency (from 4% to 21%).

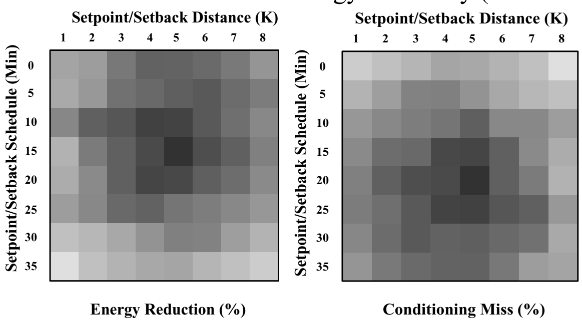

Fig. 1. occupancy transitions and energy efficiency

For *occupancy variations*, the deviation of daily real-time occupancy from the occupancy pattern was associated with energy consumption and conditioning miss. Occupancy based control (the relatively optimal combination of 15 minutes and 78F setback selected from Section 4.1) was simulated and the corresponding daily energy efficiency was calculated and compared with the average occupancy variation level of rooms on the third floor. Based on the results, there is a negative linear relationship between the occupancy variation level and HVAC energy efficiency. From a stochastic perspective, the HVAC energy efficiency for each specific day is significantly influenced by the variation of occupancy for that day (from 3% to 24%).

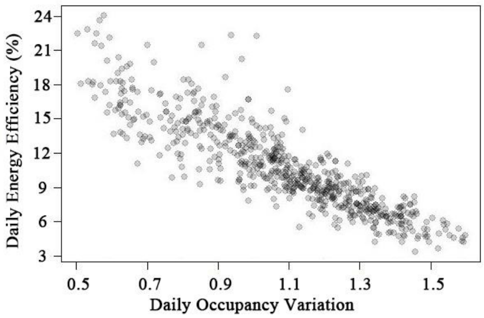

Fig. 2. occupancy variations and energy efficiency

For *occupancy heterogeneity*, occupancy profile was used as the measure to quantify the heterogeneity level of real-time occupancy, and to group similar occupancies. For a certain HVAC control policy, the energy implication of occupancy heterogeneity could be represented by the potential reduction of effective loads after conditional load redistribution by reassigning occupants at the building level. Predefined requirement constraints (e.g., room size) and capacity constraints (e.g., number or rooms within a zone) were integrated, with zone adjacency, orientation, and HVAC layout being considered simultaneously. Occupancy based control (the combination of 15 minutes and 78F setback) with current assignment was simulated for benchmarking. The occupancy based control after occupant reassignment and based on 99 random reassignment plans were also simulated. Their relative locations then represented the possibilities of influences of occupancy heterogeneity, which are significant (from 0.2% to 12%).

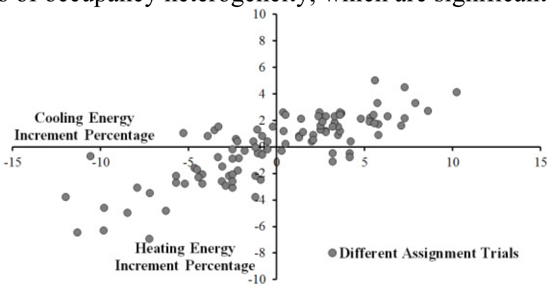

Fig. 3. occupancy heterogeneity and energy efficiency

4. Conclusions

This paper systematically investigates how the occupancy influences the energy efficiency of HVAC systems from three perspectives of occupancy transitions, variations, and heterogeneity. Contributions include a first exploration of the importance of different occupancy-load relationships for energy efficiency, and new knowledge about the influences of specific occupancy characteristics on effective

HVAC loads. It acts as the start point to dynamically couple tempo-spatial occupancy and heating/cooling loads, and provides novel trials to decompose complicated interactions among HVAC, occupancy and thermal conditions into manageable control loops. The findings of research can be used as a road map for further research. It is important to note that these investigations do not aim to provide specific control solutions for a specific building but instead seek to model the influences of occupancy on energy efficiency regardless of building or building system types.

5. Conclusions

This paper systematically investigates how the occupancy influences the energy efficiency of HVAC systems from three perspectives of occupancy transitions, variations, and heterogeneity. Contributions include a first exploration of the importance of different occupancy-load relationships for energy efficiency, and new knowledge about the influences of specific occupancy characteristics on effective HVAC loads. It acts as the start point to dynamically couple tempo-spatial occupancy and heating/cooling loads, and provides novel trials to decompose complicated interactions among HVAC, occupancy and thermal conditions into manageable control loops. The findings of research can be used as a road map for further research. It is important to note that these investigations do not aim to provide specific control solutions for a specific building but instead seek to model the influences of occupancy on energy efficiency regardless of building or building system types.

Acknowledgements

This material is supported by the U.S. National Science Foundation under Grant No. 1351701. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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Biography

Zheng Yang is a PhD candidate in Civil Engineering (Informatics for Intelligent Built Environment). His research focuses on investigations of relationships between building occupancy and HVAC loads for energy efficiency and the explorations of interactive, automated, adaptive and non-intrusive frameworks to increase building energy efficiency, occupancy and system performance awareness.